On Colour-Vision by Very Weak Light.

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In my paper on Artificial Temporary Colour-Blindness, I wrote:— "Hering's black-white sensation I have not found, but the evidence for and against it is of a somewhat different character, and I propose to discuss it in a separate paper."

Hering's theory, as is well known, rests partly on the statement that, under a very feeble illumination, all colours appear grey—that there is an interval between the chromatic threshold and the absolute threshold of light sensation—and his statement is supported by a number of experiments by various observers, which have been received as classical.

I find myself under the necessity of traversing this statement, inasmuch as in my own case, to the perfectly rested eye, red, green, blue, and violet are instantly recognised as colours and distinguished from each other, and there is no interval between the chromatic and the absolute threshold, and it is only when the eye is not perfectly rested that all colours appear grey in a feeble light.

In laying before the Society an account of the experiments which have led me to this conclusion I have endeavoured, in view of the direct conflict between my testimony and that of so many previous writers, to give sufficient details to justify my own position, and to indicate a possible explanation of these contradictory results.

Early Experiments.

Experiment 1.—The mental attitude of the observer, of comparatively little interest in other cases, has a certain importance when subjective phenomena are under investigation. For this reason my first experiment is described in greater detail than would otherwise be given.

I had been repeating, in the course of my studies, and with some success, as many as possible of the experiments referred to in my books. Among others was the statement that, with sufficiently feeble illumination, all colours appear grey. In order to observe this, I arranged a metal chimney, furnished with a cap, over a bunsen burner so as to completely prevent the escape of

light without interfering with the free supply of air. By bringing the flame near the side of the chimney, and increasing or diminishing the supply of gas, the metal could be brought to a dull red heat only just visible.

Operating at night in a room with the blinds drawn, the first appearance of luminosity was of a pearl-grey tint. Encouraged by this result, I proceeded to try how much fainter the light could be made in an absolutely dark room without becoming invisible. Accordingly, my father had the gas laid on in an inner room which had no windows. The bunsen burner, standing in the middle of the metal chimney, was lit and turned down low. After remaining in complete darkness for two hours I moved it to the side, so that the flame touched the metal, and waited. To my surprise, the first visible luminosity was dull red, instead of grey as in the previous experiment. Slightly reducing the gas supply caused it to disappear gradually, but without passing through grey.

It should be noted that I was disappointed at having obtained, after so much trouble, what seemed a worse result, and ascribed it to a too rapid raising of the temperature, but was unable by the most careful adjustment of the lamp to see any traces of the light before it appeared red. The next night, after repeating the experiment with no greater success, I went to get a screw-clamp from the outer room, which was dark save for the light of a street lamp 100 yards away, upon the canvas sun-blind, which was drawn down. After returning, the first visible luminosity was grey until I had remained in darkness another half-hour, when I could see only red, as before. My original bias being opposed to the result obtained, gives greater weight to the experiment.

In order to have another colour for comparison, I drilled a small hole in the back of the chimney on a level with the flame, the blueish light of which, received on a sheet of paper about 18 inches off, was just visible. This appeared of a rich blue tint, in strong contrast to the dark red of the metal. By varying the distance of the paper from the chimney the relative intensities of illumination could be adjusted until both reached the minimum simultaneously. But the contrast of colour was always visible, however faint the light, *when the eye was completely free from the after effects of previous stimulation.*

Experiment 2.—Glowing metal did not seem satisfactory as a source of light, because the refrangibility of the rays increasing continuously with the temperature, there must be a quantity of green rays almost capable of exciting sensation by the time the red rays were strong enough to do so. I therefore modified the experiment, using the spectra of rarefied gases because

it is easier to distinguish differences of colour between two parts of a spectrum that is not continuous.

The method, which I finally adopted, of reducing the intensity of the illumination to the requisite degree, was to vary the distance between the spark-gap, or vacuum tube, and a piece of white paper, towards which the slit of the spectroscope was directed, the whole apparatus being in the dark room, and enclosed in a box blackened inside and covered with a black cloth, through which the eyepiece of the spectroscope projected.

For bright-line spectra, it is better to have the slit rather wide. It is difficult, after staying some hours in total darkness, to tell exactly how the eye is focussed when straining to catch sight of an almost invisible object, and the intensity of the stimulus due to a small object is much diminished when the image of it, being out of focus, is spread over a larger surface of the retina. As soon as the object is caught sight of, the difficulty vanishes and the slit may be narrowed.

To locate the position of a given line, I used a broad pointer with a square end, fixed horizontally in the focal plane of the eye-piece (Fig. 1). This causes an easily visible gap to appear and disappear as it is moved to and fro over a faint line.

With this arrangement I found that lines as far in the red as that of lithium always appeared red, however faint, if the eye was sufficiently rested, and that the sodium lines were green, but that, with more eomplex spectra, the middle portions were so much brighter that it was difficult to see the ends. I therefore prepared a light-filter, composed of gelatine films stained to the requisite depth with aniline and other pink and purple dyes, painted on with a brush until the faintest visible spectrum of lamplight, seen through them, appeared no brighter at the middle than at the ends.

Fig. 1.

Experiment 3.—Using the above described light-filter, I placed in the focal plane of the eyepiece a stop with four slits so spaced as to leave visible a strip of red near B, of yellowish-green near D, of blue close to F, and of violet as far beyond G as the light employed would admit. I found afterwards that a small strip of paper covered with Balmain's Luminous Paint, aid partly across the white reflecting surface, would supply additional violet if necessary.

The illumination was made so faint that even after two hours in tota
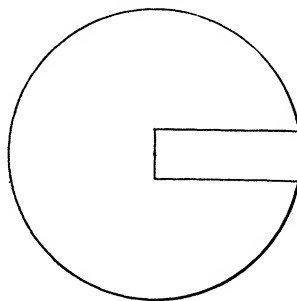
darkness I could not see the bands continuously, but could only catch glimpses of them from time to time, as one does when looking for stars in early twilight. It is very difficult to tell in total darkness in what direction to look, even with the eyebrow touching the eye-piece, so that the band first seen was seldom the one I expected to find. Yet the colour was instantly recognised.

Each colour produces a characteristic effect quite apart from tone or tint. The red band catches the eye suddenly as it sweeps to and fro through the darkness. Once seen, it is easily held for some seconds—and lost as easily. Its edges are perfectly definite against the darkness.

The blue band first shows as a blue haze, persistently appearing in one spot, and refusing to follow the eye as it sweeps across. On looking steadily the haze resolves itself into a band with fairly definite outlines. (It should be noted that the method adopted, of reducing the intensity of the light *before it enters the spectroscope,* effectually does away with the false light that is so troublesome in some cases. There is no visible "field of view.")

Violet appears first as a haze of violet after-effect, which seems to have a cumulative action with regard to the sensation it excites. It is difficult to see the outline of the band, owing apparently to its strong tendency to produce after-effects even with such low intensity. But if the eye is kept perfectly still the violet is held, when once found, even more easily than the red.

There is a curious phenomenon associated with the green that I do not understand, but have seen so often that I here call attention to it. The outline is definite though not so definite as that of the red, but the band seems to sparkle as I look at it. That is to say, it is not continuously equally bright all over, but spots of slightly greater luminosity of perhaps 5′ or 8′ diameter appear and disappear in various parts of it. Any portion of the spectrum from D to *b* will do this, but beyond *b* the steady light of the blue sensation seems to mask the effect, which is only visible when the eye is completely rested (after two hours darkness at least) and with very faint illumination—either the minimum visible or a little more.

Experiment 4.—This experiment is the converse of the preceding. I arranged a weak continuous spectrum of lamplight which, after half-an-hour's stay in darkness appeared white, or rather colourless, from end to end. After setting the broad pointer to mark the extreme limit of this spectrum towards the red, I took away the paper reflector and put the lamp in its place. What I had taken for the extreme limit of the spectrum proved to be the beginning of the red. I concluded, therefore, that the ratio of the light sensation to

the physical stimulus varies differently with the intensity for red and for green, and that it was desirable to make quantitative measurements.*

With respect to the violet end of the spectrum another difficulty arises. Paper of all kinds fluoresces strongly in the violet, giving out a light consisting largely of green, and is hence unsuitable as a reflector before the slit of the spectroscope to reduce the light. Porcelain, which does not fluoresce, does not seem to reflect much of the violet near H and K. Powdered sodium bicarbonate, pressed into a flat cake, seems as good as anything if pure.

This part of the work was done from 1873 to 1878 in my father's works at Cheshunt.

Later Quantitative Experiments.

I repeated these experiments in 1893–5 with precisely similar results, in the Physiological Laboratory, Oxford, but on referring to the literature of the subject and finding how many experiments had been published with results diametrically opposed to mine, I determined to investigate the subject yet a third time, and to obtain also quantitative measurements in regard to: (*a*) the sensitiveness of the eye to red and to blue by daylight and in darkness, and (*b*) the time-relations of the subjective phenomena which accompany a prolonged period of darkness.

This final revision of the work was begun in 1901 and, after various unavoidable delays, was completed about a month ago.

The source of light was a 16 candle-power glow-lamp placed some distance from a piece of white paper fixed at an angle of 45° outside the wall of the dark room, in which was a circular aperture 2·5 cm. in diameter. The arrangement is shown diagrammatically in Fig. 2. A is the glow-lamp, B the paper reflector, C the wall of the dark room, D a polarising prism, E the spectroscope, with F a double-image prism over the eye-piece.

In the focal plane of the eye-piece I placed a stop with two narrow slits, the distance between them being such that if the red about B was brought under one, the blue-violet about G was visible through the other. With the double-image prism the order in which the bands appeared was V_1, V_2, R_1, R_2.

Blue-violet was chosen to contrast with red because the light available was not strong in violet and I considered the relative intensity of the red and this part of the spectrum might be less affected by changes in the strength of

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* I was not at that time acquainted with Purkinje's work, with which this is in entire agreement.

the current. For the same reason I used paper instead of sodium carbonate, thus getting rid, by fluorescence, of a great part of the violet rays.

Fig. 2.
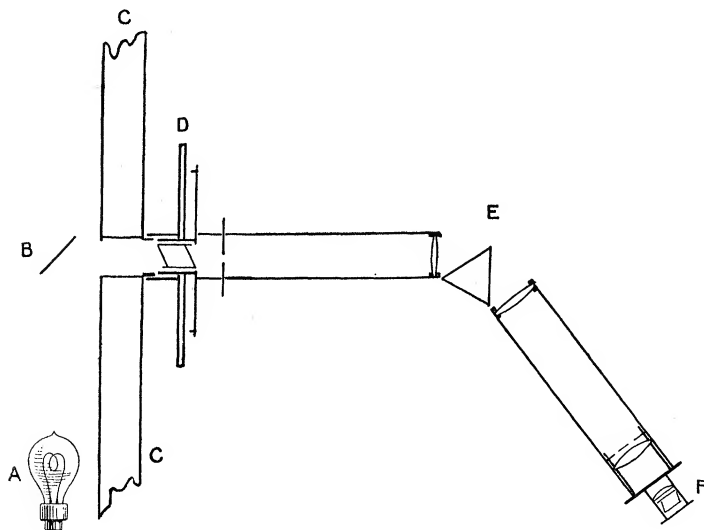
The experiment consisted in turning the polarising prism D until the blue-violet band V_2 and the red band R_1 appeared equally bright, and then altering the intensity of the light by placing the glow-lamp A nearer to or farther from the paper reflector B, and finally, if any change was observed, readjusting the polarising prism until V_2 and R_1 were again equally bright. From the data thus obtained, the relative intensities of the colour-sensations under the different degrees of illumination could be calculated.

Here some explanation is necessary. It may be objected that there can be no definite standard of equality of brightness between two different colours. That is perfectly true in the sense that not only does the position of the prism vary when it it is set by different observers, but the same observer, under different conditions of light adaptation, makes very different settings. What I here mean by "equality of brightness" between two colours is this: an observer sets the prism so that the two colours are, in his opinion, equally bright. The prism is then displaced by someone else, and the observer asked to repeat the setting immediately. He will probably do so with not more than 2 per cent. variation in the relative intensity, and generally much less. His standard of equality is personal and empirical, but it is constant so long as his physiological condition is unchanged.

It would seem that after remaining in total darkness for two hours, a fairly constant physiological condition is reached, and I have, therefore, compared all the ratios with those obtained under these circumstances.

It should be noted moreover, that the feebler the sensation the less the judgment of the observer enters into the result, until finally, when both bands are so faint that they can only just be glimpsed from time to time, the sensations may be considered equal if each is seen with equal difficulty.

In order to record a series of observations made during a long period of darkness, I devised the simple arrangement shown in Fig. 3.

FIG. 3.
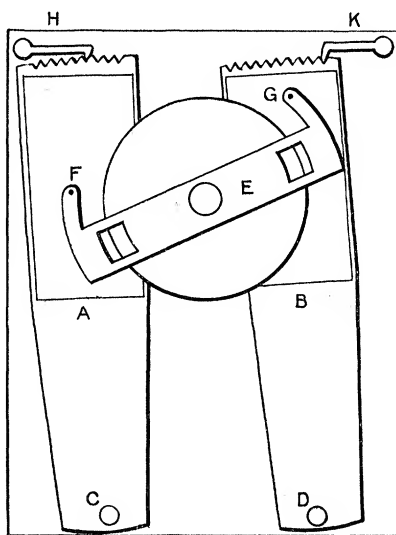
The divided circle is fixed about 5 mm. in front of a larger square plate on which two thin pieces of wood A and B, are pinned by the pivots C and D. Each piece is furnished with a notched sector of sheet brass in which the spring catches H and K engage. The brass plate E fixed to the tube containing the Nicol prism carries, in addition to the verniers, two thin springy strips of sheet brass F and G. To the end of each strip is soldered a small drawing pin carefully sharpened, and a thin card is fastened to each of the pieces A and B.

After the first observation made in the dark room the strip F is pressed so that the point marks the card. A is then moved one notch so that the mark for the next observation may come on a different part of the card. I have found it convenient to use the other spring G for recording results

obtained at the end of the period of darkness. As a check, the two positions of extinction are marked with both F and G.

After coming out of the dark room the pins are carefully adjusted to each of the marks in succession, using a magnifying lens, and the corresponding readings taken. As there is no possibility of mistaking the order in which the marks were made, owing to the cards having been moved on between each observation, the Nicol may be turned back some 20° or 30° so that there may be nothing to prejudice the observer in his next attempt. Practically I found this made no difference and is not advisable in dealing with very feeble illumination, because it exposes the eye to an image which may be several times stronger than the minimum visible.

Experiment 5.—Made at night, after walking a mile and then spending half-an-hour in the gas-lit laboratory.

Having arranged the apparatus with the room lighted, I reduced the illumination of the spectrum to the minimum visible and adjusted the Nicol till the red R_1 and the blue-violet V_2 were equally bright, and pricked a record. I then moved the lamp A (Fig. 2) so much further from the paper reflector that I could see nothing whatever in the spectroscope, shut myself in the dark room, turned out the lights, and waited. After 15 minutes I could just detect the blue-violet band, and after 30 minutes the red also was visible, the blue appearing most luminous. I then adjusted the Nicol until both were equally bright, and pricked the record.

The first record was 13°·7 and the second 37°·2 from the position of extinction of the red. The intensities of the two images were, therefore :—

$$V_2 D_1^{-2} \cos^2 13 \cdot 7 : R_1 D_1^{-2} \sin^2 13 \cdot 7 \text{ in the first case,}$$
$$\text{and } V_2 D_2^{-2} \cos^2 37 \cdot 2 : R_1 D_2^{-2} \sin^2 37 \cdot 2 \text{ in the second,}$$

where D_1 and D_2 are the distances of the lamp A from the paper in the first and second cases respectively. That is to say, after half-an-hour's rest in darkness the sensitiveness of the eye had increased to red, and had increased also to blue-violet, but in so much greater proportion that it now required 9·7 times as much red to match the feeblest visible blue as it did before the eye was rested.

Experiment 6.—Made on a dull day after a walk of three-quarters of a mile, followed by half-an-hour in the laboratory.

The Nicol was adjusted till the red and the blue-violet appeared equally bright, all the blinds being up and the gases lit. The intensity was just too low to enable me to see the cross-wires. Taking this ratio as unity, at the end of 5 minutes the red had to be increased to 6 times, and after 20 minutes

to 7·6 times its previous amount, to match the blue-violet. With a weaker
light 11·27 times the amount of red was required, and after 45 minutes, with
a still weaker light, 16·82 times the original proportion of red was required to
match the blue-violet.

This explains, I think, why the yellow of the spectrum shifts so much
towards the red end with very weak light after a prolonged stay in darkness.

Experiment 7.—In order to compare measurements made with light of equal
intensities during the progress of the change, and after the eye had reached
the constant condition, I arranged to remain continuously in the dark room
while an assistant came at stated intervals and moved the lamp from one to
another of a series of increasing distances from the paper screen. Each time
I marked the position of the prism for which the red and the blue-violet
appeared equally bright, and the final distance was the greatest at which I
could distinguish the two bands.

At the end of 45 minutes it was found necessary to bring the experiment
to a conclusion before reaching the final stage of adaptation. The assistant,
therefore, moved the lamp to each of the fixed distances in the reverse order,
and I took a record, as quickly as possible, of the setting of the Nicol for
which the colours appeared equal in brightness. The width of the slit
remained the same throughout, having been adjusted at the commencement
of the experiment so that the bands were, to the non-rested eye, of minimum
visible luminosity when equal in brightness.

In the table " Time " signifies the number of minutes after the room was
darkened. " Intensity " represents the physical intensity of the band in

During the Process of Resting in Darkness.

Time.	Intensity of red.	Intensity of blue-violet.	Ratio.	
0	3·17	103·28	31·83	Minimum visible.
5	4·34	23·49	5·41	Easily visible.
20	1·20	5·80	4·84	After blow on the eye.
30	1·14	2·19	1·93	Easily visible.
45	1·00	1·00	1·00	Minimum visible.

After Resting in Darkness.

45	1·00	1·00	1·00	
46	1·34	2·06	1·53	
47·30	1·98	5·30	2·67	
49·30	4·97	23·08	4·64	
51	11·55	97·67	8·46	

terms of its intensity when the lamp was at the greatest distance from the paper reflector, namely, 2 metres. "Ratio" is the quotient of the intensity of the blue-violet band by that of the red, and shows the proportion of blue-violet to red necessary to produce an equal sensation under the conditions of the experiment, taking as unity the ratio for the minimum visible to the rested eye.

Although the positions in which the lamp was placed for the second set of readings were the same as for the first set, the intensities are different, because in adjusting the two colours to equal luminosity by the Nicol prism, the one is increased and the other diminished. This is one of the drawbacks of the polarisation type of photometer.

The third measurement is interesting.

Moving my head towards the instrument in the dark, the cap of the eye-piece came sharply in contact with my face close to the eye. The bands, which had appeared red and blue, though barely visible, were instantly obscured by a luminous fog of after-effect, so that I could not take the reading for some 30 seconds, and when I did, they both appeared colourless.

Experiment 8.—In this case I remained more than two hours in total darkness, but did not take the first record till nine minutes had elapsed. The unit of intensity is the minimum visible at the end of two hours, *i.e.*, with the lamp 3 metres from the paper. The slit was, I believe, narrower than in the preceding experiment.

During the Process of Resting in Darkness.

Time.	Intensity of red.	Intensity of blue-violet.	Ratio.
9	16·63	254·76	15·32
21	11·14	57·61	5·17
25	4·61	12·82	2·78
60	2·40	5·39	2·24
120	1·00	1·00	1·00
After Resting Two Hours in Darkness.			
120	1·00	1·00	1·00
122	1·20	1·63	1·34
123·30	1·67	2·82	1·65
125	2·69	5·14	1·91
127	5·04	12·44	2·47
128·30	13·21	55·82	4·23
130	50·02	225·72	4·51

Between 25 and 60 minutes I ascertained that striking the forehead smartly with the hand when the bands were just bright enough to show colour caused them to appear colourless for a few seconds, but on repeating the experiment at 105 minutes this effect was no longer produced.

This result is, I consider, of great interest. For if a pair of differently coloured bands, considerably brighter than the minimum visible, appear for a few moments colourless when the after-effects of previous illumination, or dazzle-tints, receive a transient intensification, the inference is plain that the colours of the minimum visible must be far more liable to be masked even without such intensification, and that no observation as to the impossibility of distinguishing colours in the minimum visible can be valid unless it has been ascertained that the dazzle-tints have completely subsided.

Relation of the Violet-blue : Red Ratio for the Minimum Visible by Daylight, to that for the Minimum Visible after Two Hours in Total Darkness.

In making these measurements I grasped the eye-piece of the spectroscope with my left hand so as to exclude all extraneous light from the eye. The sensitiveness of the eye changes so rapidly that it is necessary to have some time limit within which the bands must be perceived. The normal limit here adopted was one minute. If they were glimpsed before 55 seconds or after 65 seconds, the experiment was rejected.

Experiment 9.—Sitting with my back to the window on a dull December day with all blinds down but one, the violet-blue : red ratio was 70.

After looking out of the window for a minute or so it was 341, and on looking at the sky, which was very dull and cloudy for 10 seconds, it rose to 418. Ten minutes' rest with my back to the window brought it to 96. After writing for about 5 minutes on white paper it was 185. Ten minutes spent talking in an upstairs room brought it to 364, and after another 10 minutes with my back to the light it was 111.

Experiment 10.—On another occasion I took a series of measurements at half-hour intervals, working in another room in the intervals. The first measurement was taken directly after setting up the apparatus, and the second after going about the laboratory collecting materials for my other work. In the former case the influence of the subdued light of the room in the basement in which the apparatus was situated is evidenced by the lower reading and in the latter the effect of the more brightly illuminated rooms is very marked. The last three, when the intervals were spent under fairly constant conditions, agree tolerably well.

Each measurement was made independently, the Nicol being turned back

Minimum Visible by Daylight, in Terms of the Minimum Visible after
Two Hours in Total Darkness.

Red.	Blue-violet.	Ratio.	
18·9	1060·4	56	After setting up the apparatus.
8·0	1070·0	134	After going about the laboratory.
14·4	1064·3	74	After working in an adjoining room.
14·0	1064·7	76	,, ,, ,,
13·1	1065·5	81	,, ,, ,,

through an unknown angle after the record was pricked. At the end of the
series of experiments the angles corresponding to all the records were read off.
As it is important in all measurements depending on sensations rather than
physical quantities to avoid mental bias, I did not, until these experiments
were completed, refer to my notes taken in 1901 of the literature of the
subject. It is the more interesting to find that, in Charpentier's case, the eye
increased in sensitiveness to white light at least a thousand times after a
prolonged stay in darkness, and on one occasion two thousand five hundred
times.

It should be observed that, in my experiments, no brighter light was used
than that of a very dull and cloudy December sky, and that only for a few
seconds. Judging from other experiments, I consider that Charpentier's
highest figures must be well within the mark for a person coming from a
fairly well-lit room in the summer time.

But it would appear that by far the greater part of this increase of sensi-
tiveness relates to the more refrangible rays. In my own experiments, the
minimum visible for blue-violet varied in daylight from 1060 to 1070 times
its value after two hours in darkness, whereas the range for the red is pro-
portionally much greater, although the largest value is barely nineteen and
the smallest eight times the minimum visible to the dark-adapted eye. This
larger value was probably due to fatigue of the red sensation induced by the
glow-lamp while adjusting the illumination.

Time-relations of the After-Images and Dazzle-Tints.

I have reserved the description of the subjective sensations experienced in
the dark room during these and other experiments, in order to discuss them
separately. The notes of these observations were written at the time, in the
dark, with pencil, in a small reporter's note-book. A fresh page was turned over

for every fresh note, an indiarubber band round those written on preventing the same page from being used twice. An account of each experiment was written in the laboratory book, while the exact significance of the notes was fresh in my mind.

Time was recorded as follows :—A shaft carrying a grooved wheel 10 cm. in circumference was connected with the arbor of the hour-hand of a common Ansonia clock, so as to revolve with it. On a thread wound round this wheel, and attached to it, hung a small weight, to the bottom of which was soldered a toothed wheel of rather larger diameter than the weight.

The whole was mounted on the top of an upright case about 18 inches high, inside which the weight hung. Before making an experiment, a strip of white blotting-paper was secured to the back of the case with drawing-pins, the weight wound up to the top by turning the hour-hand backwards, and a mark made on the blotting-paper by pressing the toothed edge of the weight against it. This mark was entered in the note-book as the zero of time.

While in the dark room, before making each note, the weight was pressed against the blotting-paper so as to mark it. Immediately after the conclusion of the experiment, the weight was wound up to each mark in succession, and the corresponding time read off on the clock face. There is no difficulty in reading to 30 seconds, and there is ample space for a 3 hours' record. Except in a vague way, the observer does not know how the time is going on. If it were desirable to keep him in entire ignorance of it, an electrical time-marker might be used to record on smoked paper. I used this clock during each of the above-described experiments, and during many others made solely for the purpose of investigating the time-relations of these subjective phenomena.

The phenomena succeed one another in a well-marked order, but at no fixed time. As in the case of the duration of artificial colour-blindness,* and also of the rate at which flickering ceases for the various colours in experiments by intermittent light,† not only the condition of the eye as regards previous fatigue, but also the state of the health seems to exert a considerable influence on the time required for the eye to become completely rested. There are, however, very noticeable time-relations between the various stages of the process which preserve a certain proportionality among themselves.

Actual after-images—the ocular spectra of Newton—do not as a rule last more than 10 minutes or a quarter of an hour, unless they have been excited by looking for some time at a strong light, in which case they may

* 'Phil. Trans.,' B, vol. 191, 1899, p. 1.
† 'Journal of Physiology,' vol. 21, 1897, p. 426.

come up again and again in the most unexpected manner, after remaining invisible for half an hour or more. On one occasion, on my way to the laboratory, I had for some minutes watched a bird nest-building in a tree. After turning out the gas in the dark room I saw after-images of the flame for about 10 minutes. These died out, and for some time the room seemed full of a luminous fog. Then gradually an image of the branches round the birds' nest developed, and persisted with more or less distinctness for nearly three-quarters of an hour. Under such circumstances, it is seldom worth while continuing the experiment, as the concluding stage is likely to be correspondingly delayed. It is better to avoid looking at the sky or any bright light for some hours before entering the dark room.

If this precaution is taken, the average course of events is fairly shown by the following figures taken from seven experiments, in which the final stage was reached in two hours. The times given are the earliest and latest at which the phenomena described commenced in any of the seven experiments :—

0 to 5 minutes. Confused after-images of portions of objects recently looked at. These images, with the exception, perhaps, of that of the gas or lamp flame, do not usually appear for the first 20 or 30 seconds after the light is turned out. They have hard outlines, and they gradually fade and give place to a luminous fog, made up of what I have called " dazzle-tints," *i.e.*, coloured impressions of luminosity without form.

10 to 15 minutes. Fog no longer uniform, but "spotty" with patches of a brownish or greenish-bronze colour.

18 to 21 minutes. A group of yellow or green luminous points—10 to 15 of them, arranged quincunx fashion, floats about, following the direction of the eyes. This phenomenon is, I believe, associated in some way with the yellow spot. It occurred in five out of the seven cases, lasting from 10 minutes to half-an-hour.

23 to 28 minutes. Green " dazzle-tints " predominate, beginning to break up, in some cases, into patches of green showing a fainter blue between.

40 minutes. Blue increasing—green weakening and breaking up into isolated patches.

66 to 72 minutes. The luminous fog, which now shows no trace of green, begins to break up into blue patches, with occasional black spaces between.

Generally after this, for a while it seems as if all the after-effects had gone. But on making a great effort of attention it becomes evident that they are still there.

Swinging the arms, or going through dumb-bell exercises will bring them back for a time.

106 to 120 minutes. Gradually a luminous violet fog seems to fill the surrounding space. For a minute or two it increases in brightness, and then breaks up near the middle in two or three places and seems to roll away on all sides.

Then it returns, and again breaks up, generally leaving an island about the size of the yellow spot, which lasts two or three seconds longer than the rest. The colour of these clouds is a rich pure violet like that of the calcium lines H and K in the arc spectrum. This phenomenon may go on from 10 minutes to half-an-hour, the violet patches getting smaller and appearing at longer intervals till they die away. When that has happened no more "dazzle-tints" appear, and in my own case *there is no longer any interval whatever "between the absolute and chromatic thresholds."*

In other words, green is distinct from blue, and blue from violet, and violet from red as soon as either is strong enough to produce any sensation at all.

I desire to emphasize this conclusion. It is absolutely opposed to the statements of Hering,[*] Hillebrand,[†] Aubert, Charpentier,[‡] Landolt,[§] Vogel[||] and others, whose experiments have been regarded as classical. But it is the result of experiments made in the first instance with a mental bias in favour of the view I am opposing, and finally repeated with the improved appliances now at my disposal.

The times given above represent the normal duration of the various stages in the fading out of the after-effects of light upon the eye.

They are seldom shorter, but occasionally much protracted.

Sometimes the red "dazzle-tints" return after more than half-an-hour, and the green persist correspondingly longer. In 1895 several times I waited for nearly three hours without getting beyond the green. In January of the present year, on one occasion the green "dazzle-tint" persisted for 75 minutes instead of being quite gone at 40 minutes. I therefore discontinued the experiment because it would probably have involved waiting about four hours for the violet to pass off.

After-effects last longer in summer than in winter, perhaps partly because of the greater brightness of the daylight and its longer duration. As a rule I find them more persistent during ill health, but on one occasion, after anæsthetisation of the eyeball by cocaine, I saw the violet clouds one hour after the bandage had been put on, *i.e.*, one-half the usual interval.

In view of this great variation in the time required for the subsidence of after-effects, it is quite conceivable that with some persons they may persist

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* Hering, "Untersuchung eines total Farbenblinden," 'Pflüger's Archiv,' vol. 49, pp. 563 to 609.

† Hillebrand, "Specifische Helligkeit der Farben," 'Wien Akad. Sitzber.,' 1889, p. 70.

‡ Charpentier, 'Thèse de Doctorat,' 1877 ; also 'La Lumière et les Couleurs.'

§ Landolt, 'Comptes Rendus,' vol. 86, p. 495, 1878.

|| Vogel, 'Annalen d. Physik u. Chemie,' 1895, vol. 54, p. 745.

so long as to be practically never absent. And in such cases there would always be, as some observers have maintained, an "interval between the absolute and the chromatic images." When my eyes have not quite lost the "dazzle-tints" there is, to me also, such an interval. But when they are completely rested there is none.

Experiment 11.—According to the theory of Young and of Helmholtz, each portion of the spectrum with the exception of its two ends, excites more than one colour sensation. My own experiments on artificial colour blindness support this view. The observations recorded in the present paper show that the effect of rest in darkness is to increase the sensitiveness of the eye very much more to the highly refrangible than to the less refrangible rays. It follows that a colour like that of the sodium flame which, to a normal eye, excites the red and green sensations in almost equal proportions will, if the intensity is greatly reduced and the eye sufficiently rested, excite a larger proportion of green. This I have put to the test of experiment. The results are interesting as bearing on the precautions necessary in such cases. A Bunsen flame in which was a piece of glass tubing containing crystals of sodium thiosulphate was placed at such a distance from a paper screen outside the dark room, that its light, reflected on to a second piece of white paper inside the dark room in the place usually occupied by the spectroscope, was barely visible to the perfectly rested eye. *It appeared whitish-grey even when considerably brighter than the minimum visible.* The reason of this was evident when I removed the second paper reflector and examined the light from the first with the spectroscope. In addition to the sodium lines there was the spectrum of the Bunsen flame itself with its three bands in the green, the blue, and the violet. But in the spectroscope, where these other colours were separated from them, the *sodium lines appeared pale green when of the minimum visible intensity.*

The sensitiveness of the eye to blue increases so greatly after two hours in darkness that nothing but spectrum analysis can ensure its absence—and a very small trace may suffice to change orange to white. For the same reason we cannot take the green of the spectrum at E or *b* as the standard green for the minimum visible. We know that the red and the blue sensations overlap there, even if the violet does not reach so far. The colour must look pale under feeble illumination owing to the presence of three if not all of the constituents of white. The greatest contrasts seem to be obtained, so far as I have gone, with light from B for the red, from D for the green, from F for the blue, and from H and K for the violet.

Owing to this overlapping of the colours, I have not yet satisfactorily

determined the increase in the sensitiveness of the rested eye to green. It appears to be less than the increase for blue.

There is no colour about which so much latitude of expression is used as about white. Being composed, according to Newton's view, of all the colours, it is more affected by variations in the composition of the light than, for instance, red, which may appear brighter or darker, but cannot change its hue. We habitually discount this effect in the case of white, without doing so for the other colours. Thus purple flowers often look red by lamp-light, and are spoken of as red; but white paper, though it looks yellow, is called white. And we do so whether using candles, arc lights, or incandescent gas, though the actual hue of the paper is different with each, and is strikingly so when they are compared side by side with daylight. With regard to the colour or colourlessness of very feebly illuminated objects, no experiment should be considered valid in which the colours are not contrasted. None but spectral colours should be used, and even these, owing to the overlapping of the colour sensations, must of necessity appear pale. Few persons have the faculty, which dyers by long practice develop, of being able to match colours by memory. Yet this is what has to be done in order to say, after two hours in absolute darkness, whether a colour so faint as to be barely visible is pale yellow, pale green, or pale blue.

To sum up :—In my paper on Artificial Colour-Blindness, I described experiments showing that Hering's argument in favour of a black-white sensation is invalid, in so far as it rests on the statement that by intense light all colours tend towards white. For the apparent whiteness—in the green region, for instance—is only a transitory stage in the production of green blindness, and is reached when the green sensation is reduced to the strength of the underlying blue and red, the mixture of the three being equivalent to white by candlelight, and, therefore, by courtesy, white. And if we continue the experiment the whiteness gives place, as the eye becomes completely green-blind, to rich red and blue.

I submit that the experiments described in the present paper indicate that Hering's theory of the black-white sensation is also invalid in so far as it rests on the statement that by very faint light all colours appear white.

For in this case also my experiments, many times repeated and extending over a number of years, show that the apparent whiteness is only a transitory stage in the recovery from the after-effects of light, and is due largely to positive as well as negative after-effects. And when the " dazzle-tints," as I have called them, have completely subsided, there is no interval

between the threshold of light-sensation and the threshold of colour-sensation.